Development and Assessment of an Experimental System for Swarm Formation by Underwater Robots

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Abstract—To examine swarm formation, we developed a system comprising a set of robots, a position acquisition system, a visible light communication device, and a PC to obtain the position and orientation of the respective robot and to determine their motion. Using it, experiments were conducted on the ground and underwater. Results of the experiments show that the system can make the robots form a predefined formation on the ground. They can move two underwater robots to target points. Results show that the system is useful to develop and to verify swarm algorithms in a realistic situation, not merely in a computer simulation.

Index Terms—underwater robot, swarm, visible light communication, control system

I. INTRODUCTION

In nature, creatures such as fish, birds, and insects form swarms to increase their capabilities. Some fish and birds swarm to obtain their food efficiently and to reduce risks of being captured by predators. Some insects such as ants and bees swarm to divide their tasks and improve mutual cooperation. Such creatures have no strong ability to survive in nature alone; some insects do not even have reproductive capabilities. They swarm to survive as a species.

Some researchers have studied swarm formation. Bluefin tuna detect other individuals by vision and lateral line feeling. Then they swarm and school by contact sensor. Then they verified that communication of nearby creatures. Thereby, a swarm forms.

Many researchers have modeled creature behavior in swarm formation. A well-known model is Boids by Reynolds \cite{2}. Each Boid follows three simple rules: Separation, Alignment, and Cohesion. Each simulated creature behaves independently based on the behaviors of nearby creatures. Thereby, a swarm forms.

In recent years, many robots have been developed to perform information gathering during times of environmental research. Most such robots are large, are intended to perform individually, and consist of many complicated units. Therefore, damage that occurs when losing a robot according to some failure or an accident is severe.

Swarm robots are anticipated for use as a countermeasure against these problems. Each robot has a few simple functions. Their low-grade capabilities are compensated by swarm formation. They perform missions as a group. Creating and using one robot can be inexpensive, thereby minimizing damage to its owner if it is lost. Moreover, these robots can perform missions efficiently by allocating a portion of a task to each robot and by sharing the information that each robot collects.

Fujisawa and others \cite{3} proposed an algorithm of robot behavior using pheromone-like behavior of ants. They verified the validity of the motion through numeric simulation. They also developed 10 robots, each with a pheromone sensor, a light sensor, and a contact sensor. Then they verified that communication using a pheromone works effectively.

Inada and others \cite{4} examined a method that was suitable for control of a set of MAVs, and developed a behavior model based on three rules—‘Approach’, ‘Parallel orientation’ and ‘Repulsion’—which are modeled after swarm formation by creatures. Their simulation showed that the objects performed as a swarm even if some objects were lost. They also showed that the motion and formation of the swarm is controllable by controlling only a few of the objects.

Arima and others \cite{5} modeled the cooperative operation of an underwater robot, presuming application of a model to an underwater glider. They introduced a blackboard agent on which the robots can read and write information, and conducted a simulation of the routing of the robots. Results showed that the robots perform cooperative operations by specifying the simple rule of following the shortest course from a present location to a destination. They also showed that it is effective to use a blackboard agent in situations where communications are restricted, as they are underwater.

These study results suggest the effectiveness of the swarm model for underwater robots. However, although applications to systems on the ground have been performed, they have not been conducted for

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underwater robots, perhaps because of the restricted use of a sensor or a communication facility.

For this study, we developed a control system that is applicable to the study of swarm formation. Results of a preliminary study were reported earlier [6].

II. MATERIALS AND METHODS

A. Conceptual Design of the Control System

For this study, we develop an underwater robot control system to reproduce swarm action.

For many robots, aiming at research of swarm action, each robot determines its operation using a sensor and a communication device. However, in this study, swarm action is reproduced by determining the operation of each body with an external control system. Manufacturing a system that can investigate many swarm action algorithms is easy using this method.

This system acquires position information related to each body through image analysis from the space outside of operation, determines the operation of each body from position information, and sends an actuating signal to each body via communications apparatus.

With the system and a subject using this control system, it seems possible to identify various problems that might occur. Fig. 1 and Fig. 2 respectively show a schematic diagram and detailed configuration of a control system.

This system identifies each body using image processing software and acquires a robot’s position and direction. It determines the operation of each body using information related to this position and direction. Algorithms for system experiments can be used with it.

In this research, to confirm the control system operation, we implement an algorithm for an operation experiment. This algorithm avoids contact of bodies and determines operations corresponding to the arbitrary destination points that are set up beforehand.

B. Position Acquistion and Communication Systems

This control system must acquire multiple robots’ position information. To acquire each robot’s position information, QPToolkit [7] image-analysis software is used. QPToolkit recognizes multiple markers that are registered from video images beforehand, calculates the positions and orientations of the markers from these positions, orientations and sizes in the video image, and outputs them using TCP/IP communication. Each robot's position information is acquired by attaching a marker, which differs for each robot.

A so-called web camera (HD Pro Webcam C910; Logitech International S.A.) is used to acquire marker positions throughout experiments. This camera has a USB connector for communication and power supply, which is connected to a PC on which a QPToolkit runs.

The preliminary experiment in the ground shows that this software can detect a position with sufficient accuracy to at least 3 m in the depth direction of a camera. At the depth point of 2.5 m, it turns out that it can measure within 1.1 m and 0.8 m in the horizontal and vertical directions of a camera, respectively. We create mapping formulae between the measured position by the QPToolkit and the real world and use it on the occasion of experiments.

As a means of underwater communication, it is common to use ultrasonic waves. However, they are inappropriate for our system, which consists of multiple robots, because ultrasonic sensors for underwater use are expensive. Therefore, we use visible light communications (VLC) in this control system. The VCLs are easily and cheaply realizable using a fundamental electronic circuit. Moreover, if an underwater robot is created for transparent materials such as an acrylic resin, then a receiver can be installed inside of a robot so that it is not necessary to expose it underwater.

For communications, a PC sends a robot’s operation command to a communication control unit (Arduino [8] microcomputer board). This board blanks an LED according to an operation command and transmits a signal. Serial communication is used for communication between the PC and a microcomputer board.

Fig. 3 shows a unit of a VLC transmitter. We install several units in experiment space and send a command to the robot, which carries a phototransistor (receiver).

C. Control Program and Operation Algorithm

A control program acquires each robot’s position information by TCP/IP communication using a QPToolkit, determines each robot’s operation, and sends commands to the robots using the VLC signal transmitter.

To verify the control system operation, we develop a simple algorithm of the operation using the programming language Processing. Fig. 4 shows the screen of a control program of operation. We choose a simple and easy-implementable algorithm for verification purposes. The main concern of this research is development of the experimental system, not the algorithm.

This program assumes that each robot has four degrees of freedom: three for position and one for direction on the level plane.

When moving a robot to a target point, a robot first turns to head to a target point. Then it moves to the point. When a robot collides by the middle, the system sends commands for the robots to stay away from each other to a certain distance. After that, the robots resume their operation to move to the target points. In addition, when the system cannot recognize a robot marker, as in the case where the robot hides behind other robots and is not visible from the camera, the system sends a command to stop the robot in its current position.

The system controls all robot motions. The case when a robot cannot receive the VLC signal is the sole exception. The algorithm for that case is explained later.
D. Preliminary Ground Experiments

A preliminary experiment was performed on the ground to investigate the possibility of controlling multiple robots with the system.

Fig. 5 presents an outline of an experimental device. Fig. 6 shows the experimental apparatus. On the ground, it performs two-dimensional operation. Therefore, a camera for image analyses is installed above the operation space. A marker is stuck on the robot's upper surface. Consequently, marker overlapping does not occur.

We develop and use five robots for this experiment. Fig. 7 shows the robot for a ground experiment. Fig. 8 presents its configuration. This robot has two tires that are driven independently by two motors to perform forward and backward motions, rotation, and their combinations. It also has a VLC receiver (phototransistor). This experiment is aimed at operating these robots and for producing multiple formations one by one.

The system judges that the robot arrived at the target point when the distance from the center of the robot (marker) to a target point is less than 50 mm. In the case in which a robot cannot obtain signals from the controller, the robot continues to perform the previous motion. No emergency algorithm is implemented.

E. Underwater Robots and Experimental Apparatus

An underwater experiment is conducted using the system and underwater robots. Fig. 9 presents a schematic diagram of the experiment. Fig. 10 shows a photograph.

To verify the control system operation, we develop and use the underwater robots shown in Fig. 11. Fig. 12 presents its system structure.

This robot has a couple of independently driven thrusters (screw propellers) for propulsion, and a couple of thrusters for up-and-down motion. It performs forward and backward movement, rotation in the vertical axis, diving and surfacing movement, and their combinations. It also has a VLC receiver (phototransistor) and receives operation commands.

In the case in which a robot cannot obtain signals from the controller, the robot first simply stops the motion and waits (e.g. 10 s). Then it descends to the bottom because, in experiments, it obtains signals better near the bottom than near the surface. Subsequently, the robot tries to ascend to the surface to be collected.

III. RESULTS

A. Preliminary Experiments on the Ground

Fig. 13 presents images of robot formations on the ground. In the ground experiment, it was observed that the system controls the five robots and makes the robots form different formations one-by-one. In Fig. 13 (b) and (c), the robots take the same formations 5 times respectively, changing positions counterclockwise. Fig. 14 depicts the path of the robot No. 2 (left bottom one in Fig. 13 (a)). The robot first approaches the initial position to form a line. After that, it shows the circular motion and then the square motion as depicted, respectively, in Fig. 13 (b) and (c).

The VLC system controls the robots successfully at 9600 bps within the field of 1 m × 1 m. Because the amount of transmitted information is less than 10 bytes (100 bits including start and stop bits) for each robot at a time, this transmission speed is sufficient.

The system includes an algorithm by which the robots which approach each other too closely head in the opposite direction from one another (repelling operation). Fig. 15 shows an image in which the robots are mutually repelling.

Robots can collide during operations. Fig. 16 presents an image of robot collision. In this case, robots approach each other. Then the head parts of robots collide. The head part is the furthest point of the robot from the marker center. Therefore, it seems that the cause of collision is that the predefined distance to perform a repelling operation is too small.

B. Underwater Experiments

In underwater experiments, the system can induce two robots to move to arbitrary positions. Fig. 17 and Fig. 18 portray images showing two robots in operation. We control a robot three-dimensionally within the field of 1.5 m × 1.5 m. The VLC system sends commands to the underwater robots at the speed of 9600 bps when the robots are near the bottom. If the robot is near the water surface, then the robot sometimes moves the positions between the units of transmitters so that it cannot receive signals. Therefore, we control the robots to move near the bottom.

More than two robots, however, cannot be operated properly in underwater experiments. Although the robot's actuator (propeller) operates, the robot does not move. Therefore, it turns out that, although the position recognition and the communication systems function correctly, the robot's propellers do not produce sufficient thrust to move properly. Two better-constructed robots can move underwater, but others cannot.

In addition, when a robot arrives at a target point, it does not stop at the point but passes through it. Fig. 19 shows images in which the robot passes the target point so that the robot continues to oscillate around the target point. Fig. 20 shows a time history of the robot oscillation. The oscillation amplitude is about 100 mm.

In this experiment, the robot does not slow if the target point is approached. The actuator continues functioning until the robot reaches the point.

In the experiment on the ground, the robot stops at the target point. It seems to do so because of friction with the ground. Underwater, the robot does not stop without effort because the influence of inertia is dominant. Therefore, it is necessary to use control to stop a robot at a target point in an underwater experiment.
IV. DISCUSSION

For this experiment, we developed a simple algorithm to operate the robots. A problem arose related to the setup of an algorithm of the operation. This result suggests that this control system provides an effective method to develop and verify swarm algorithms. In addition, in the experiments, inadequate operation sometimes occurred because of undesirable conditions and disturbances of the robots.

Using this control system is apparently superior to a computer simulation because problems that are unique to a real system can be observed. ‘Real’ motions such as collisions and inertial motions of robots are readily reproducible by the system. Simulations do not reproduce such phenomena unless all physical laws are implemented appropriately.

In underwater experiments, each robot implements an emergency operation in case the robot does not receive signals over a certain period of time. It seems effective to delegate the greater part of control to each robot.

Four screw propellers are installed on each robot as actuators for propulsion, diving, and surfacing motions. These actuators entail various problems such as waterproofing and output adjustment. With a small underwater robot operating at shallow depths, it seems that fin propulsion is better than that with screw propellers.

We have gained experience through construction of several robots that have fin actuators [9]. Such actuators can be implemented using a servomotor, a crank mechanism, and waterproofing boots, and without submerging a motor unit in water. An important shortcoming is that fin vibration might cause vibration of the marker, thereby making image recognition difficult.

In some cases of underwater experiments, the system sends inappropriate commands to a robot because of robot marker recognition errors by the image analysis program. Therefore, it is desirable to take some measures to elucidate recognition errors.

The view of the camera and the range of the VLC light limit the experimental field size. Increasing the numbers of cameras and VLC transmitters is expected to expand the field.

V. CONCLUSIONS

We developed an experimental system that realizes underwater swarm motion. It consists of a set of robots, a communication device, a position and orientation acquisition program, and a control algorithm. Experiments conducted on the ground and underwater produced the following conclusions.

1. The five robots of this system perform swarm motions on the ground.
2. This system controls two underwater robots to move to a target point.
3. This system is effective for the development and verification of an algorithm of underwater swarm formation.

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REFERENCES


Fig. 1. Schematic showing swarming robot control system.
Fig. 2. System hardware and software configuration.

Fig. 3. Elemental unit of visible light communication transmitter attached with floating materials.

Fig. 4. PC screen image of working control system.

Fig. 5. Schematic showing experimental system on the ground.

Fig. 6. Photograph of experimental system on the ground.

Fig. 7. Experimental robot on the ground.

Fig. 8. System configuration of the experimental robot on the ground.

Fig. 9. Schematic of underwater experimental system.
Fig. 10. Photograph of the underwater experimental system.

Fig. 11. Experimental underwater robot.

Fig. 12. System configuration of the experimental underwater robot.

Fig. 13. Examples of robot formations on the ground.

Fig. 14. Path of a robot in the ground experiment (Robot No. 2 in Fig. 13).

Fig. 15. Motion of robots trying to prevent collision.
Fig. 16. Robot collision.

Fig. 17 Image of underwater experiment. This image was taken with a camera for observation (“Camera for REC” in Fig. 9(a)) so that the viewpoint differs from those of Fig. 18 and Fig. 19.

Fig. 18. Examples of two underwater robots in motion, taken with an underwater camera for computer vision.

Fig. 19. Examples of robot motions. The robot does not stop at the target point but passes through it.

Fig. 20. Time history of operating robot height, as measured from a movie image such as Fig. 17.